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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 978

PERFORMANCE TESTS OF WIRE STRAIN GAGES

II - CALIBRATION FACTORS IN COMPRESSION

By William R. Campbell
National Bureau of Standards

Washington
September 1945

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SUMMARY

Results of calibrations in axial compression over the strain range 0 to 0.0021 are presented for 15 types of single element multistrand wire strain gages. The majority of gages showed significant differences between the calibration factors for strain increasing and strain decreasing. Zero shift and nonlinearity between gage output and strain were present in nearly all gages. Improvement in gage performance after prestraining was apparent in most cases. The maximum difference between the calibration factors for the gages of a given type and the average factor for that type ranged from 1 percent or less for the gages of types B, M, and N to more than 4 percent for the gages of types E, G, I, K, and L.

INTRODUCTION

This report covers one phase of a series of performance tests on wire strain gages of types currently used in large numbers to measure stresses in aircraft structures. The purpose of the tests is to make available information on the properties, accuracy, and limitations of various multistrand, single element gages.

The performance test program has been divided into several phases the results of which are being reported individually. The first phase of the program, calibration factors in tension, has been reported in reference 1. The present paper reports on the second phase, calibrations under axial compression at strains between 0 and 0.0021. The effects of high strain, temperature, humidity, finite width, thickness, and rigidity on gage performance are to be considered in later reports.

This investigation, conducted at the National Bureau of Standards, was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics.

SYMBOLS

K calibration factor of a wire strain gage for uniaxial stress producing a strain ϵ parallel to the gage axis and a strain $-\mu\epsilon$ transverse to the gage axis

K_u calibration factor for strain increasing

K_d calibration factor for strain decreasing

ϵ change in axial strain

$\frac{\Delta R}{R}$ relative change in resistance of wire gage (ΔR is the change in initial gage resistance R due to change in axial strain ϵ)

DESCRIPTION OF STRAIN GAGES

Six aircraft companies, the Ames Aeronautical Laboratory, the Baldwin Locomotive Works, and the Chrysler Corporation contributed a total of 120 gages of 15 different types (A, B,... G, H-1, I, ..., O) which in all but one case are identical with the gage types reported in reference 1. The exception is gage type H-1 which was substituted by the maker for gage type H. Table 1 of reference 1 gives a description of the test gages, and figures 1 and 2 of reference 1 show the gages attached to test strips used in the tensile calibrations. Data on gage type H-1 are given in appendix I.

ATTACHMENT OF GAGES

Each maker was asked to attach eight gages of each type of his make to a test column furnished by the National Bureau of Standards, using his own preferred method of attachment. The test column (fig. 1) consisted of an 11-inch length of 2-inch square 24S-T aluminum-alloy bar stock with ends ground flat, parallel, and perpendicular to the column axis, and sides ground flat and parallel. After attachment of gages, the test column was returned to the National Bureau of Standards for gage calibrations.

Each maker was asked not to apply any loads to the test column in order that all gages would be received at the National Bureau of Standards in a virgin condition.

CALIBRATIONS

The gages were calibrated by measuring relative changes in resistance $\Delta R/R$ corresponding to known changes in strain ϵ. The calibration factor was defined by

$$K = \frac{\Delta R}{R} \frac{1}{\epsilon} \tag{1}$$

The relative changes in resistance $\Delta R/R$ were measured for strains between 1×10^{-4} and 21×10^{-4}. The lower limit of 1×10^{-4} corresponded to the initial load holding the test column between the heads of the testing machine. The upper limit of 21×10^{-4} was chosen to be inside the linear portion of the stress-strain curve of the test column.

Calibration factors K were determined as the slope of a straight line fitted by least squares to a plot of $\Delta R/R$ against ϵ. It follows that K denotes the slope at all points on the calibration curve only as long as $\Delta R/R$ changes linearly with ϵ; K denotes a mean slope in the presence of nonlinearity between $\Delta R/R$ and ϵ.

CALIBRATING EQUIPMENT

Strain Measurements

The calibrating strain applied to each wire gage was measured with a Tuckerman optical strain gage having a 0.4-inch lozenge and a 3-inch gage length. (See fig. 2.) The same Tuckerman gage was used for each of the 120 wire gages calibrated.

Resistance Measurements

The percentage change in resistance of each test gage during calibration was measured with a Wenner-type direct-reading ratio set, in a direct-current Wheatstone bridge using a high sensitivity moving coil galvanometer as a null indicator.

A circuit diagram of the Wheatstone bridge is shown in figure 3. The arm R of the bridge represents the test gage and the arm T, the temperature compensating gage. The arms A and B represent the two arms of the ratio set which is shown in figure 4. The construction of the ratio set and its use in the bridge circuit to measure percentage change in resistance of the test gage have been described in reference 1.

The combined sensitivity of the bridge and galvanometer (fig. 4) was such that at a scale distance of 2 meters, with the galvanometer critically damped, a lack of balance of 1 part in 1 million produced a scale deflection of approximately 2 millimeters upon reversal of the battery current. The voltage drop across the test gage during all calibrations was 0.75 volt.

TEST PROCEDURE

The same test procedure was followed in calibrating all gages except those of types C and H-1, which were calibrated without temperature compensation. (See appendix II.)

The test column A (fig. 5) upon which eight gages were attached, was mounted between ground loading blocks in a 200,000-pound testing machine. A plaster-of-paris cap was cast between the upper loading block and the head of the testing machine to distribute the load uniformly. An initial load of 2000 pounds was gradually applied to the column as the plaster set to fix the column in position. The Tuckerman strain gage B was then mounted on the column so as to span one of the wire gages and contact the column at points equidistant from the transverse center line of the strain-sensitive wire grid. (See figs. 2 and 5.)

A second column C, upon which was attached one gage of each type calibrated, was placed on the platen of the testing machine beside the test column for temperature compensation. The appropriate gage on column C was used as the compensating gage (bridge arm T) during the calibrations of the gages on column A. A 2-inch Tuckerman strain gage D was attached to the compensating column C. This gage was read at the beginning and at the end of each calibration to estimate the magnitude of errors in the calibrating strain caused by differential expansion between the Tuckerman gage B and the test column as a result of the gradual change in temperature in the insulated test room.

The procedure for calibration was identical with that of reference 1. With the bridge initially balanced, known resistance changes were set on the A-arm dial switches of the ratio set, the load on the column was increased until the output of the wire gage rebalanced the bridge, and the strain at the instant of balance was measured with a Tuckerman strain gage. The load was increased until the strain at the gage was 20×10^{-4} ($\pm 0.7 \times 10^{-4}$). The load was then decreased and the strain measured for the same bridge settings as for increasing load.

After the first gage on the column was calibrated, the Tuckerman gage was transferred to the other gages and the calibration procedure repeated for each gage.

ACCURACY

The accuracy of the calibration factors depends, according to equation (1), on the accuracy in the measurement of relative change in resistance and the accuracy in the measurement of change in strain.

It is estimated in reference 1 that the total error in calibration factor due to inaccuracy in the measurement of resistance did not exceed 0.1 percent.

The error in calibration factors due to inaccuracy in the measurement of strain acting along the strain-sensitive element of the wire gage is difficult to estimate.

The Tuckerman strain gage spanning the wire gage was calibrated repeatedly with an interferometer over the portion of the reticule scale used during the tests of the wire gages. Four calibrations were made; the first one before tests, the second and third calibrations after tests on 5 and 10 types of gages, respectively, and the fourth after completion of tests. No single calibration factor differed from the average factor by more than 0.068 percent. No single observation differed from the calculated autocollimator reading by more than 0.010 divisions, corresponding to a strain of 1.3×10^{-6} for the gage length and lozenge combination used. The error in calibration factor from this source would be, therefore, of the order of 0.1 percent if the strain-sensitive grid of the wire gage occupied the exact gage length of the Tuckerman gage and if both the Tuckerman gage and the test column remained at exactly the same temperature, thus eliminating differential expansion as a source of error.

Actually the strain-sensitive grids were less than one-half as long as the gage length of the Tuckerman gage. Consequently, there may be small errors due to nonlinear variations in strain along the test column within the gage length. A strain survey of a test column loaded as in the calibrations (and also loaded with intentional eccentricities) indicated that nonlinear effects would introduce errors the order of magnitude of which did not exceed 0.2 percent.

The error due to differential expansion of the Tuckerman gage and the aluminum-alloy surface to which it was attached was estimated to be not greater than 0.3 percent.

Combining the errors in both measurements of resistance and of strain, it was estimated that the total error in calibration factor did not exceed ±0.5 percent.

Examination of the consistency of the data obtained leads to an estimated error in calibration factor of the order of ±0.3 percent.

RESULTS

Gage resistances and calibration factors defined by equation (1) are given in table 1. Two calibration factors are given for each gage tested; K_u for increasing strain, and K_d for decreasing strain. Each of these calibration factors was determined as the slope of a least squares line fitted to a plot of $\Delta R/R$ against ϵ for strain increasing and strain decreasing, respectively.

The experimental data are presented in the form of strain deviation curves (figs. 6 to 20) to magnify the deviations from the linear relationship given by equation (1). The method of obtaining the strain deviation curves is described in reference 1. The curves bring out clearly the nature of the deviation from nominal linear behavior. Hysteresis is indicated by the width of the loop in the deviation curve, zero shift by the opening of the loop at the bottom, and deviation in calibration factor from the average value K_m by the tilt of the deviation curve relative to the vertical axis. Gage numbers, appearing above each curve, indicate the order in which the gages were calibrated. Gage 1 was calibrated without preloading, gage 2 after 1 cycle of preloading, gage 3 after 2 cycles, and so on with gage 8 being calibrated after 7 preloading cycles.

Table 2 shows the maximum spread in strain deviation obtained from figures 6 to 20 as the width of a vertical band just enclosing all points. The gage types are arranged in order of increasing spread.

Figures 21 to 23 show the calibration factors for the individual gages plotted against gage number and preloads.

DISCUSSION

The calibrations have shown several performance characteristics which in varying degrees are common to all the gages tested. Examination of the deviation curves of figures 6 to 20 shows that in every calibration the curve for strain decreasing from the maximum value deviated from the curve for strain increasing by an amount greater than the experimental scatter of measurements. Because of this deviation there was a zero shift after a cycle of loading which ranged from -31×10^{-6} to more than $+120 \times 10^{-6}$. The linearity between gage output and strain was generally better for decreasing strain than for increasing strain. There was a general improvement in performance after preloading; the deviation was consistently smaller for gage 8 with 7 cycles of preloading than for gage 1 with no preloading.

Figures 21 to 23 show that some types of gages had a much smaller scatter in calibration factor than other types. The maximum difference between the calibration factors for the gages of a given type and the average factor for that type ranged from 1 percent or less for gages of types B, M, and N to more than 4 percent for gages of types E, G, I, K, and L.

Table 2 shows that the spread in strain deviation for the first four types of gages differed less than 45 percent from the minimum spread of 32×10^{-6} (1.6 percent of the calibrating strain range) for gages B while that of the last three types was more than five times as great.

Table 3 gives a comparison of the average calibration factors for the tensile calibrations of reference 1, $K_{m(t)}$, with the average calibration factors of the present compression calibrations, $K_{m(c)}$. The table shows that the average calibration factors of 10 of 14 types of gages were from 0.0 to 1.8 percent lower in compression than in tension. Of the 4 types of gages showing larger factors in compression than in tension, 2 types were observed to have relatively large variations in calibration factor from gage to gage, and the average compression factors for the 2 remaining types were nearly identical to the average factors in tension. The difference between the average factor in tension and in compression was in all cases less than the variation in calibration factor from gage to gage for a given gage type.

All gages showed a positive zero shift except gage N which consistently gave a negative zero shift on the first loading cycle. (See fig. 19.) Gage N had shown this same exceptional behavior in the tensile calibrations of reference 1. The gage was attached with Duco cement as were 10 other types of gages. It differed from the remaining gages in being wound with a special wire (isoelastic). This indicates that the zero shift and hysteresis found in all wire gages cannot be ascribed entirely to the bonding material, but that it may be due in part to the wire itself.

Comparison of the deviation curves of reference 1 (tension) with the present deviation curves for compression shows that there is no marked difference in the nature and magnitude of the deviations for the two directions of loading. The gages performed in compression with the same order of accuracy as that found for the tensile calibrations.

CONCLUSIONS

The majority of gages showed significant differences between the calibration factors for strain increasing and strain decreasing. Zero shift and nonlinearity between gage output and strain were present in nearly all gages. Improvement in gage performance after prestraining was apparent in most cases. The maximum difference between the calibration factors for the gages of a given type and the average factor for that type ranged from 1 percent or less for the gages of types B, M, and N to more than 4 percent for the gages of types E, G, I, K, and L.

A comparison of the average calibration factors in compression with the average calibration factors in tension (reference 1) showed the majority of gages to have slightly lower factors in compression than in tension. The difference between these averages, however, was less than the variation in calibration factor from gage to gage for all gage types. A comparison of deviation data for calibrations in tension and in compression indicated no marked difference between gage performances in tension and compression.

National Bureau of Standards,
Washington, D. C., November 7, 1944.

REFERENCE

1. Campbell, William R.: Performance Tests of Wire Strain Gages. I - Calibration Factors in Tension. NACA TN No. 954, 1944.

APPENDIX I

DESCRIPTION OF GAGE H-1

Gages of type H-1 are shown attached to a test column in figure 24. The tape cover has been removed from the gage on the right. The following data are given to supplement table 1 of reference 1 on "Description of Gages."

Gage type	Nominal dimensions		Approximate length of grid (in.)	Wire material	Cement	Type of winding	Nominal resistance (ohms)
	Length (in.)	Width (in.)					
H-1	1.72	0.40	0.83	Advance	Duco	Grid	120

APPENDIX II

NOTE ON THE CALIBRATION OF GAGES C AND H-1

Gages of types C and H-1 were calibrated without temperature compensation. In both cases a Rubicon resistance decade was used in the bridge circuit for the T-arm (fig. 3) in place of a compensating wire strain gage. It is believed that the resulting error in calibration factor is insignificant in view of the high degree of constancy of ambient temperature ($\pm 0.3^{\circ}$ C) in the test room and in view of the lack of response of the test column, with its large mass, to rapid changes in temperature.

The temperature compensation had to be omitted in the case of gages C because the difference in the resistances of the test and compensating gages exceeded the difference of 2 percent allowed in designing the bridge.

In the case of gages H-1 temperature compensation had to be omitted since the maker did not supply additional gages for this purpose.

TABLE 1.- RESULTS OF TESTS

Gage type	Gage number	Resistance, R (ohms)	Calibration factors		K_u/K_d	Number of preloads
			Increasing strain, K_u	Decreasing strain, K_d		
A	1	122.5	2.008	2.019	0.995	0
	2	122.2	2.051	2.049	1.001	1
	3	122.1	2.006	2.012	.997	2
	4	120.5	2.011	2.019	.996	3
	5	121.5	2.034	2.031	1.001	4
	6	122.0	2.043	2.035	1.004	5
	7	120.7	1.988	1.999	.994	6
	8	121.9	2.040	2.040	1.000	7
B	1	100.1	2.068	2.073	.995	0
	2	99.9	2.086	2.089	.999	1
	3	99.9	2.081	2.078	1.005	2
	4	100.1	2.093	2.083	1.001	3
	5	99.8	2.083	2.079	1.004	4
	6	100.0	2.085	2.093	.996	5
	7	100.0	2.082	2.081	1.000	6
	8	99.9	2.084	2.072	1.006	7
C	1	87.4	1.998	2.046	.977	0
	2	87.8	2.045	2.038	1.003	1
	3	89.4	2.047	2.041	1.003	2
	4	89.4	2.036	2.032	1.002	3
	5	87.6	2.022	2.042	.990	4
	6	87.6	2.051	2.057	.997	5
	7	87.3	2.011	2.014	.998	6
	8	89.5	2.049	2.038	1.006	7
D	1	120.4	2.055	2.064	.996	0
	2	120.4	2.069	2.063	1.003	1
	3	120.5	2.072	2.069	1.001	2
	4	120.6	2.069	2.064	1.003	3
	5	120.3	2.038	2.060	.989	4
	6	120.6	2.062	2.070	.997	5
	7	120.3	2.057	2.061	.998	6
	8	120.4	2.066	2.068	.999	7
E	1	399.2	2.076	2.107	.985	0
	2	400.0	2.113	2.171	.973	1
	3	399.3	2.025	2.024	1.000	2
	4	399.4	2.046	2.034	1.006	3
	5	399.0	1.979	1.955	1.012	4
	6	399.3	2.084	2.080	1.002	5
	7	399.6	2.134	2.122	1.006	6
	8	399.1	2.058	2.067	.996	7

TABLE 1 (Continued)

Gage type	Gage number	Resistance, R (ohms)	Calibration factors: Increasing strain, K_u	Calibration factors: Decreasing strain, K_d	K_u/K_d	Number of preloads
F	1	120.5	2.007	2.028	0.990	0
	2	120.3	2.048	2.055	.997	1
	3	120.5	2.019	2.030	.995	2
	4	120.3	2.022	2.031	.996	3
	5	120.5	2.022	2.040	.991	4
	6	120.5	2.038	2.042	.998	5
	7	120.5	2.033	2.034	.999	6
	8	120.5	2.043	2.041	1.001	7
G	1	120.2	2.238	2.379	.941	0
	2	120.3	2.380	2.428	.980	1
	3	120.3	2.410	2.438	.989	2
	4	120.3	2.387	2.398	.995	3
	5	120.2	2.299	2.293	1.003	4
	6	120.4	2.322	2.329	.997	5
	[1]7	120.1	———	———	———	6
	8	120.3	2.347	2.354	.997	7
H-1	1	120.0	1.993	2.012	.991	0
	2	119.9	1.966	1.963	1.001	1
	3	119.9	1.959	1.964	.997	2
	4	119.7	2.005	2.010	.998	3
	5	120.1	1.936	1.945	.995	4
	6	119.9	2.004	2.012	.996	5
	7	120.0	2.013	2.011	1.001	6
	8	120.1	2.020	2.021	.999	7
I	1	120.1	2.025	2.041	.992	0
	2	120.2	2.149	2.148	1.001	1
	3	120.1	2.150	2.149	1.001	2
	4	120.1	2.136	2.137	.999	3
	5	120.2	2.136	2.152	.993	4
	6	120.2	2.139	2.143	.998	5
	7	120.4	2.123	2.122	1.000	6
	8	120.1	2.149	2.136	1.006	7
J	1	300.4	2.036	2.073	.982	0
	2	300.7	2.057	2.057	1.000	1
	3	301.0	2.030	2.026	1.002	2
	4	299.8	2.080	2.087	.997	3
	5	300.6	2.099	2.086	1.006	4
	6	300.7	2.078	2.077	1.000	5
	7	300.5	2.088	2.083	1.002	6
	8	300.6	2.081	2.084	.998	7

[1]No calibration factors because of excessive nonlinearity.

TABLE 1 (Continued)

Gage type	Gage number	Resistance, R (ohms)	Calibration factors		K_u/K_d	Number of preload
			Increasing strain, K_u	Decreasing strain, K_d		
K	1	50.0	2.150	2.164	0.994	0
	2	50.0	2.167	2.171	.998	1
	3	50.0	2.149	2.146	1.001	2
	4	49.9	2.164	2.162	1.001	3
	5	50.1	2.041	2.058	.992	4
	6	50.0	2.068	2.068	1.000	5
	7	50.0	2.154	2.164	.995	6
	8	50.0	2.155	2.156	1.000	7
L	1	119.5	2.286	2.306	.992	0
	2	119.5	2.340	2.345	.998	1
	[1]3	120.1	------	------	------	2
	4	119.7	2.371	2.434	.978	3
	5	120.1	2.227	2.230	.999	4
	6	119.8	2.374	2.447	.970	5
	7	120.9	2.305	2.315	.996	6
	8	119.6	2.324	2.333	.996	7
M	1	119.7	1.959	1.955	1.002	0
	2	119.9	1.970	1.973	.999	1
	3	120.1	1.952	1.961	.995	2
	4	119.8	1.971	1.974	.998	3
	5	120.3	1.941	1.959	.991	4
	6	120.2	1.940	1.959	.991	5
	7	120.1	1.957	1.972	.992	6
	8	120.3	1.958	1.962	.998	7
N	1	505.1	3.477	3.425	1.015	0
	2	504.3	3.483	3.449	1.010	1
	3	505.9	3.484	3.450	1.010	2
	4	506.2	3.472	3.452	1.006	3
	5	505.0	3.479	3.443	1.011	4
	6	505.9	3.480	3.445	1.010	5
	7	504.4	3.474	3.444	1.009	6
	8	506.6	3.472	3.443	1.008	7
O	1	100.0	2.046	2.072	.987	0
	2	100.1	2.103	2.095	1.004	1
	3	100.2	2.086	2.095	.996	2
	4	100.0	2.095	2.101	.997	3
	5	100.1	2.109	2.106	1.001	4
	6	100.4	2.100	2.096	1.002	5
	7	100.5	2.076	2.075	1.001	6
	8	100.1	2.077	2.084	.997	7

[1]No calibration factors because of excessive nonlinearity.

TABLE 2.- SEQUENCE OF GAGES IN ORDER OF INCREASING STRAIN DEVIATIONS FROM AN AVERAGE STRAIGHT LINE

Gage type	Total range of strain deviations[1]
B	32×10^{-6}
N	35
D	41
F	48
M	51
A	56
J	62
O	63
C	70
H-1	82
I	119
K	121
E	>187
L	>200
G	>200

[1]Width of a vertical band enclosing all points in each of figs. 6 to 20.

TABLE 3.- COMPARISON OF AVERAGE CALIBRATION FACTORS IN TENSION AND IN COMPRESSION

Gage type	Average calibration factors		$\left[1 - \frac{K_{m(t)}}{K_{m(c)}}\right] 100$
	Tension[1] $K_{m(t)}$	Compression $K_{m(c)}$	
A	2.027	2.024	-0.1
B	2.083	2.082	.0
C	2.034	2.035	.0
D	2.058	2.063	+.3
E	2.104	2.067	-1.8
F	2.037	2.033	-.2
G	2.314	2.357	+1.8
[2]H	1.943	-----	----
[2]H-1	-----	1.990	----
I	2.149	2.127	-1.0
J	2.088	2.070	-.9
K	2.170	2.134	-1.6
L	2.243	2.331	+3.8
M	1.980	1.959	-1.1
N	3.480	3.461	-.5
O	2.086	2.089	+.1

[1]Computed from table 2 of reference 1.

[2]No compression factors were obtained on gage H due to the manufacturer's substitution of gage H-1 (on which no tension factors were obtained).

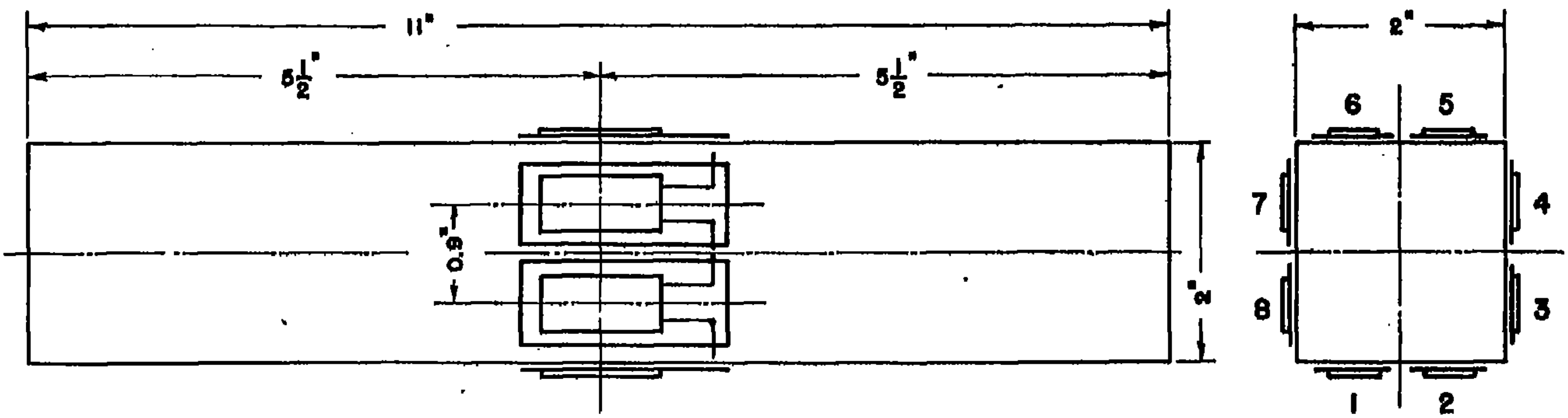


FIGURE 1.– TEST COLUMN SHOWING LOCATION OF WIRE STRAIN GAGES.

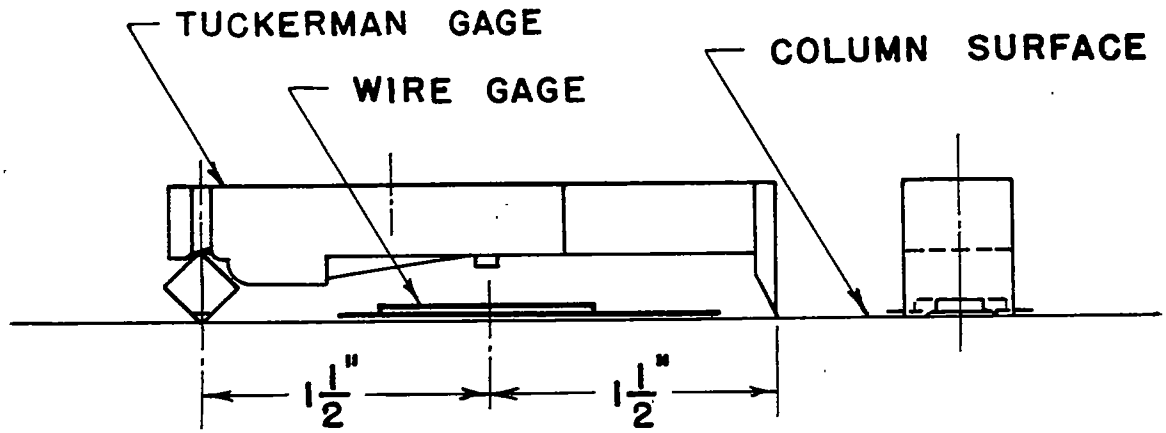
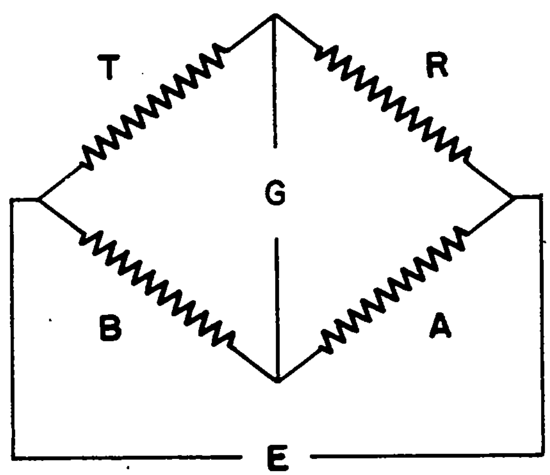


FIGURE 2.- POSITION OF TUCKERMAN STRAIN GAGE DURING CALIBRATIONS.



R AND T DENOTE THE TEST AND COMPENSATING WIRE STRAIN GAGES RESPECTIVELY.
A AND B REPRESENT THE TWO ARMS OF THE RATIO SET.

FIGURE 3.- WHEATSTONE BRIDGE FOR RESISTANCE MEASUREMENTS.

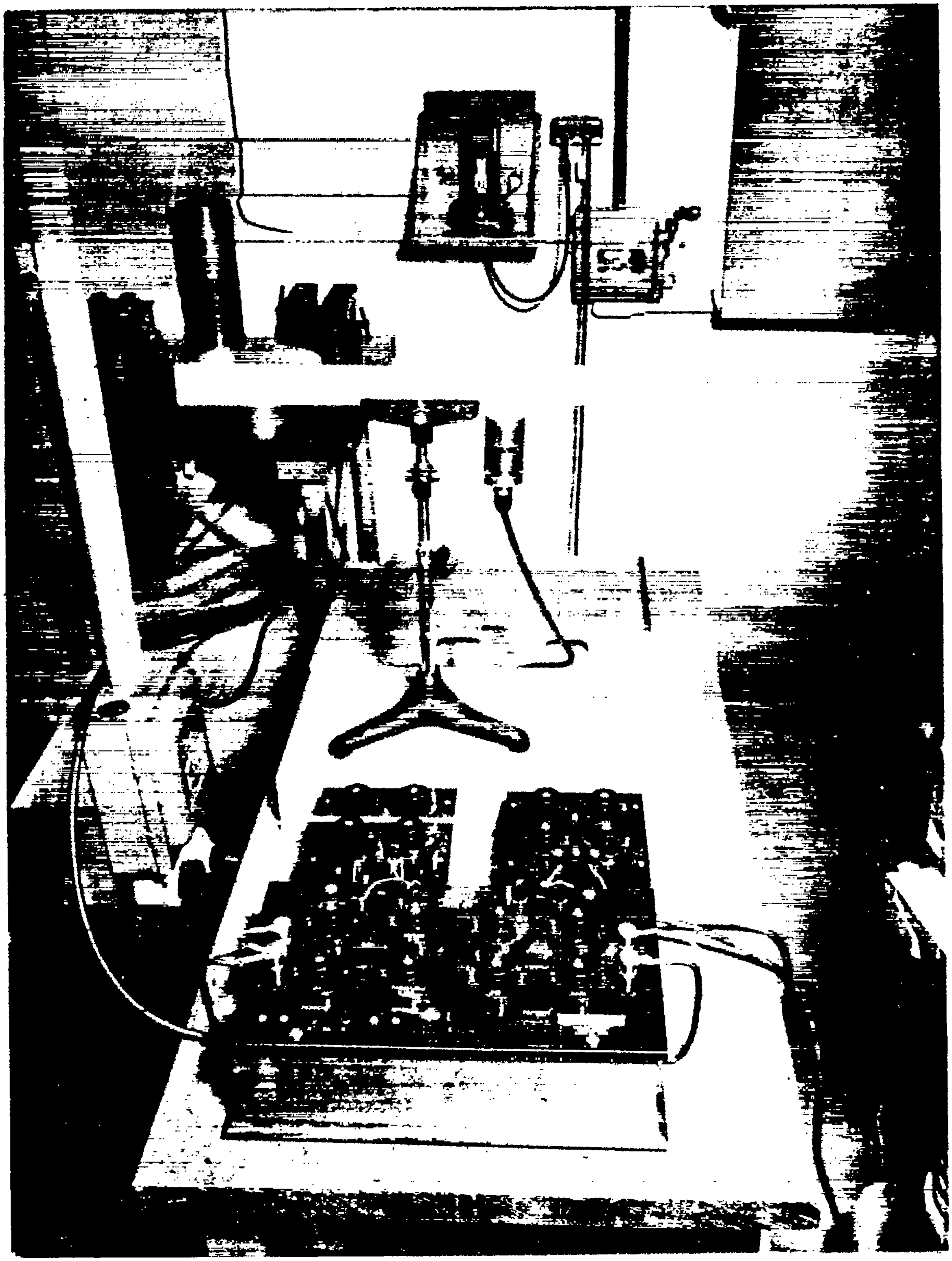


Figure 4.- Laboratory set up for resistance measurements.

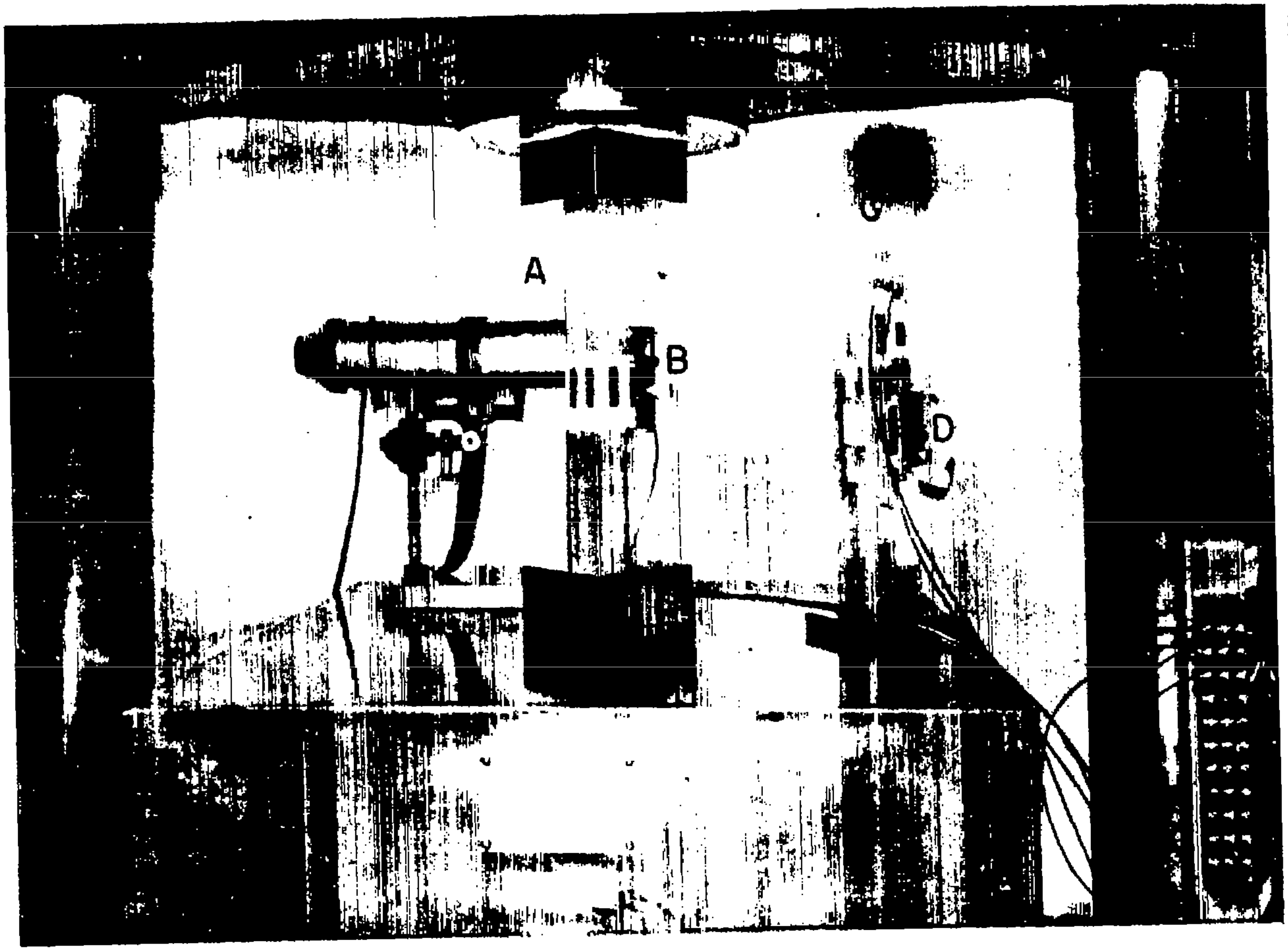


Figure 5. - Laboratory set up for strain measurements.

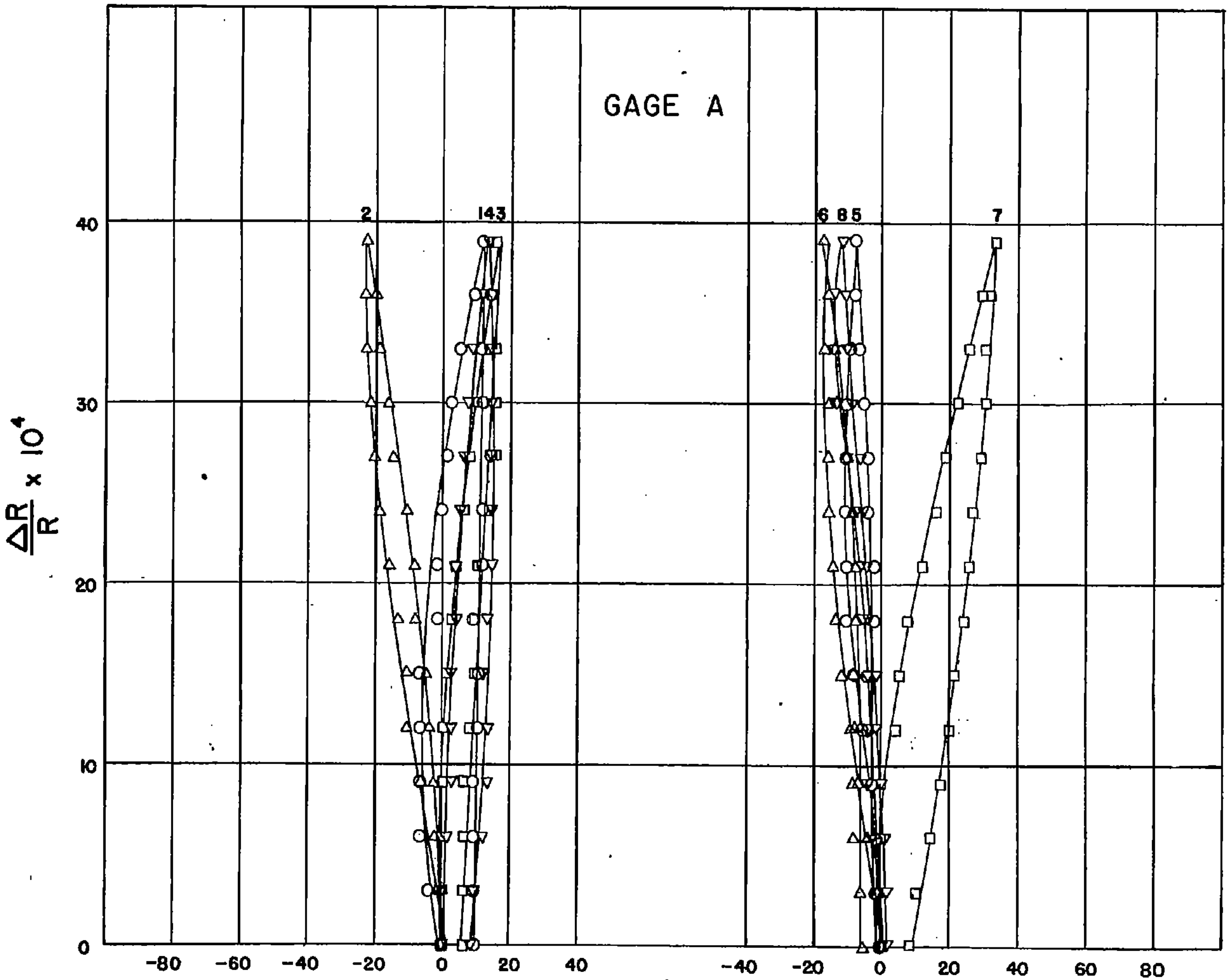


FIG. 6 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

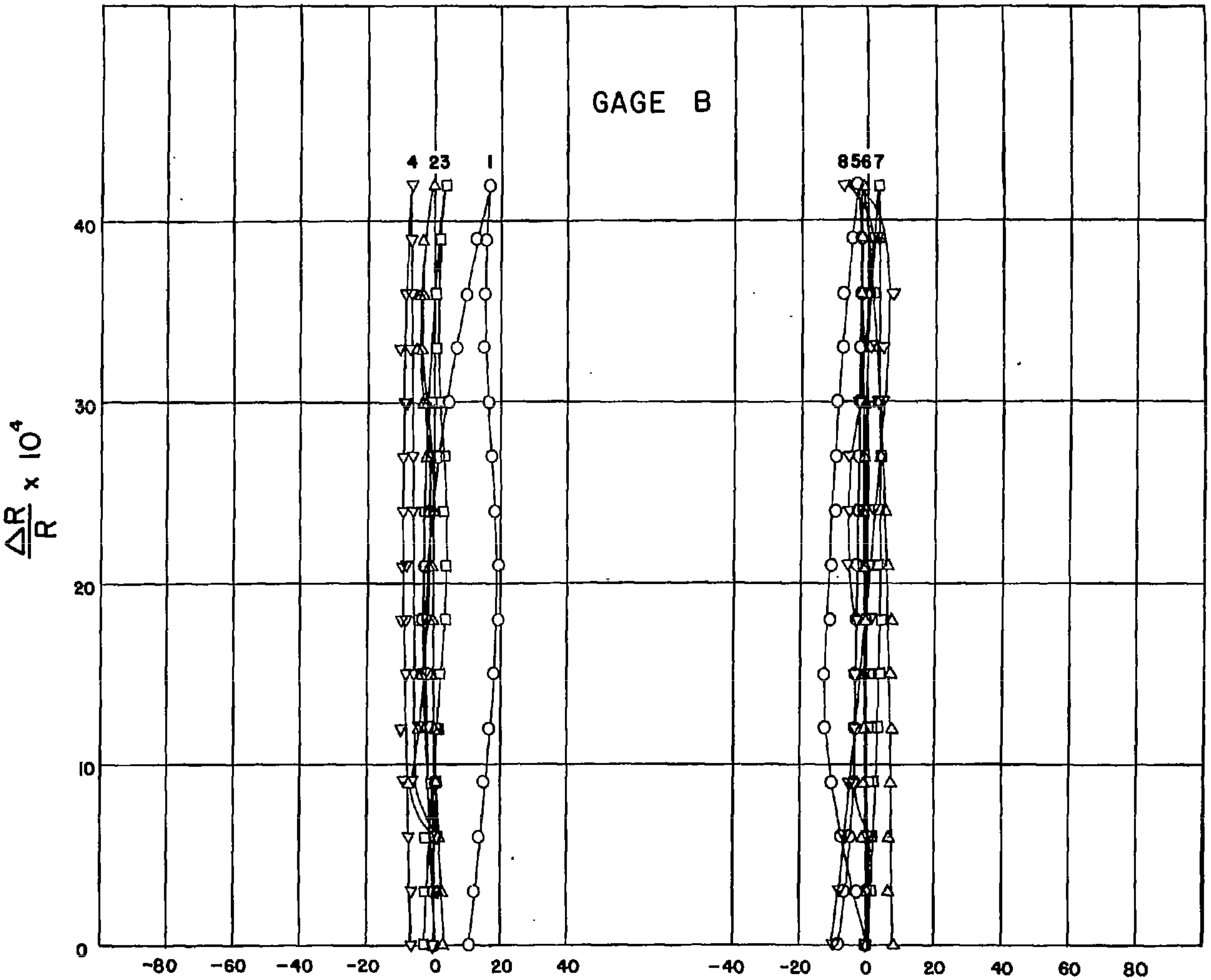


FIG. 7 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

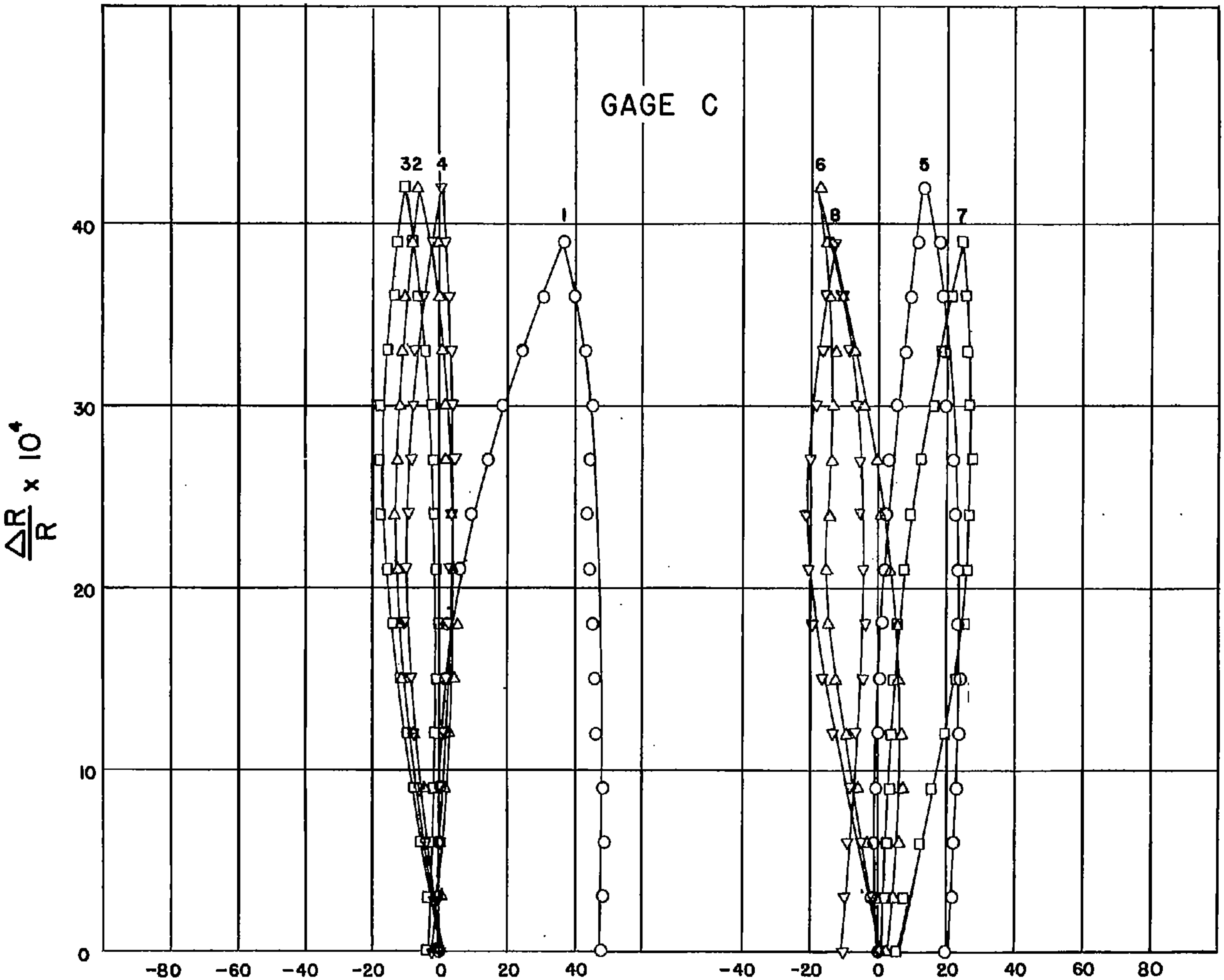


FIG. 8 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

FIG. 8

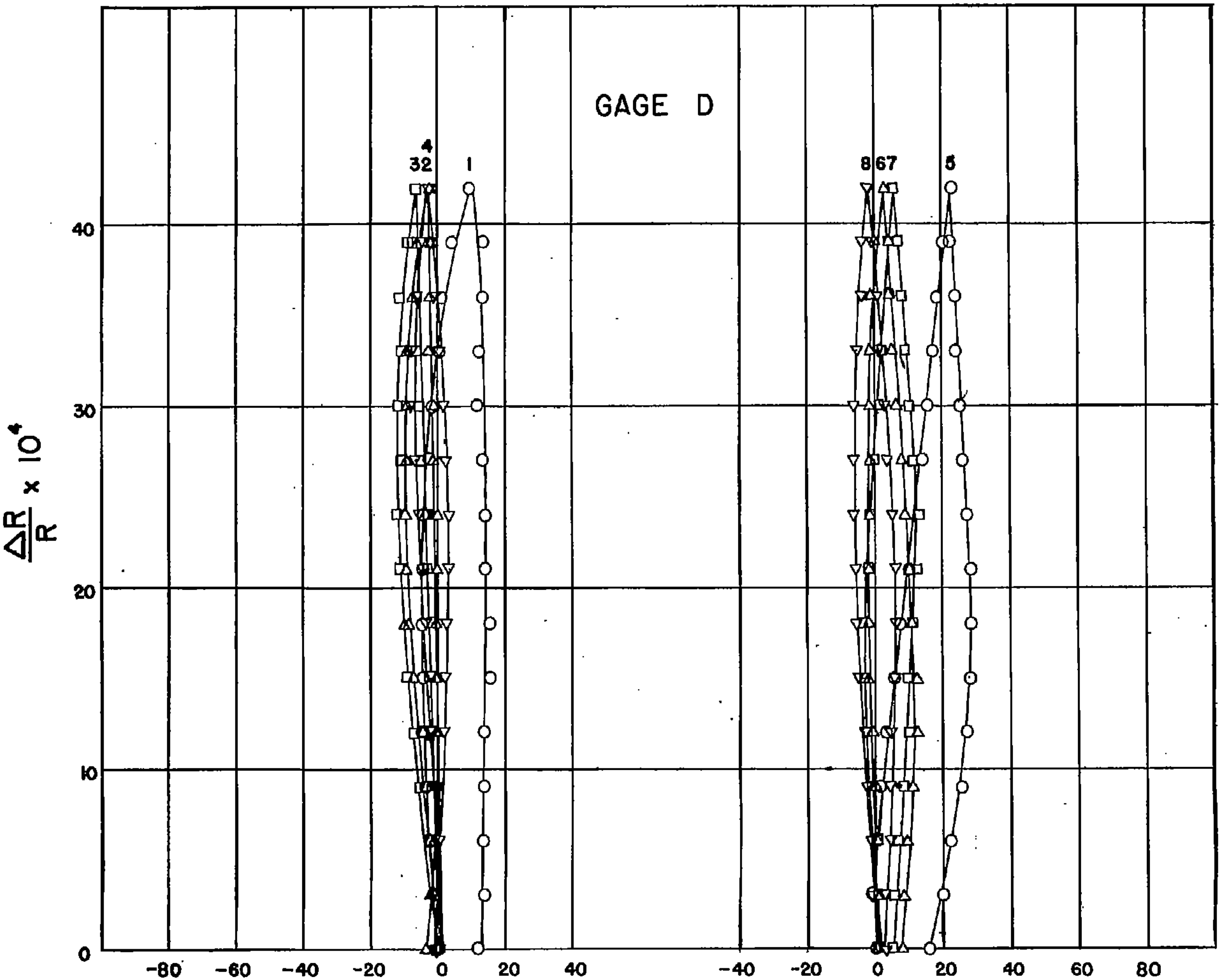


FIG. 9 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

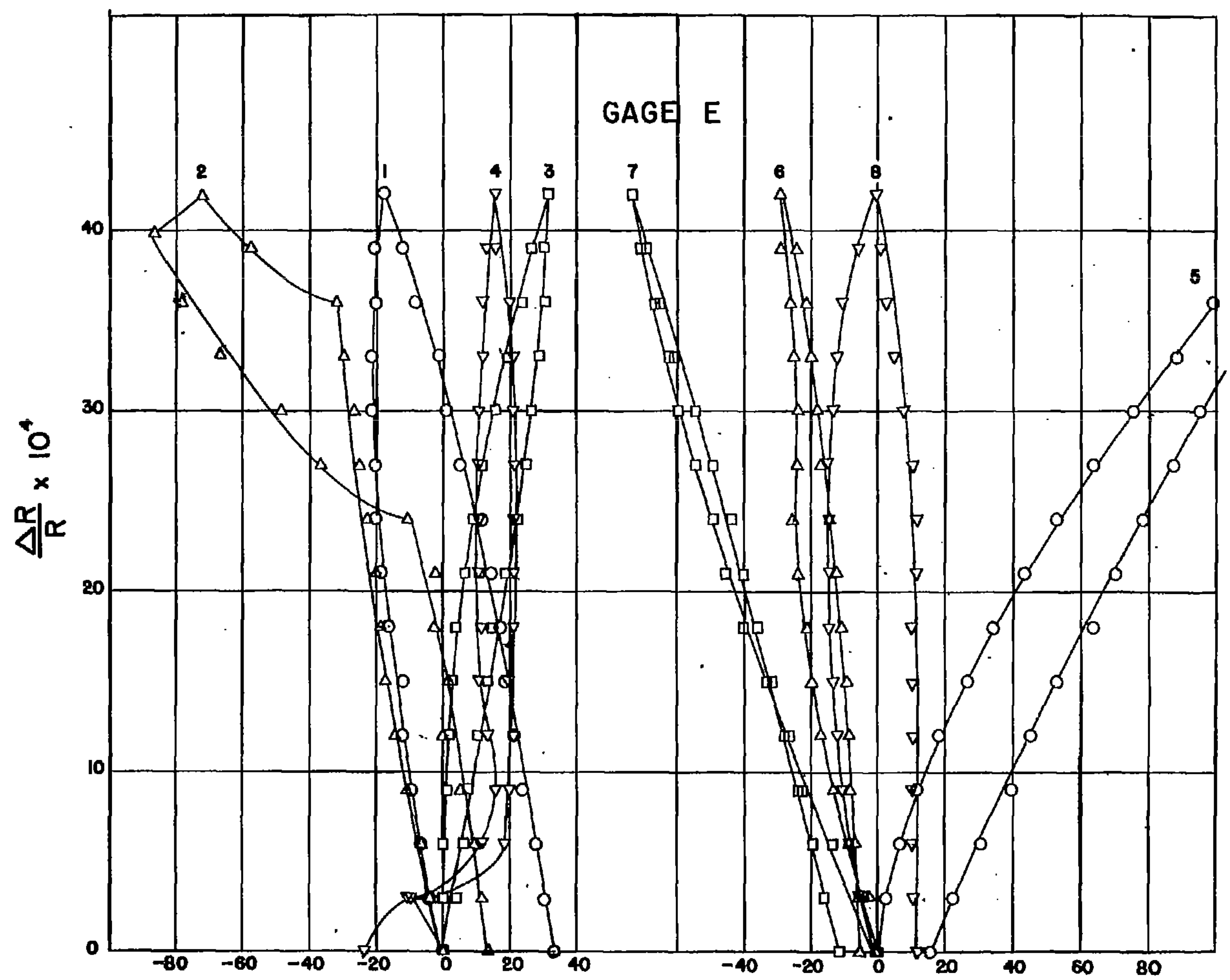


Fig. 10 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

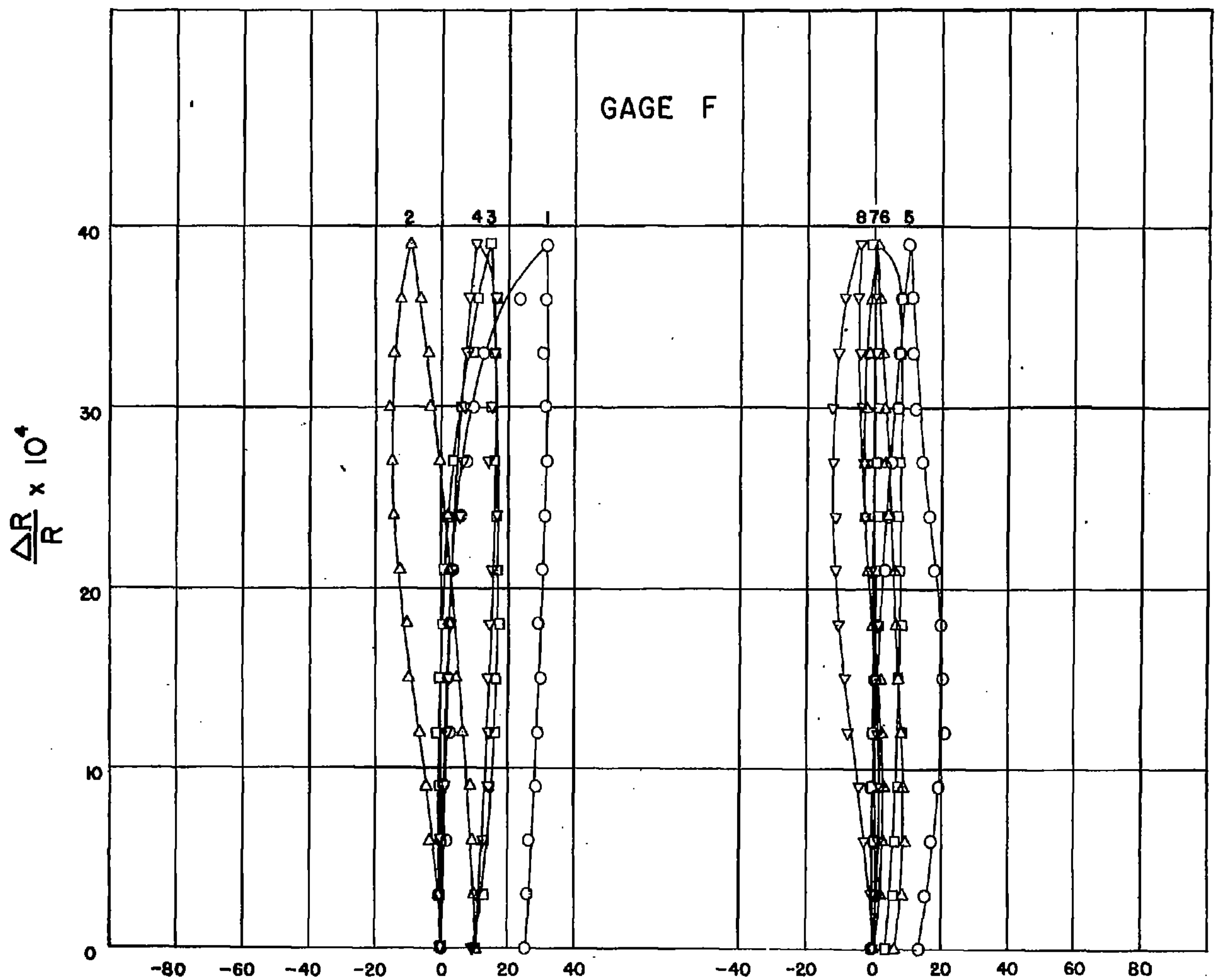


FIG. 11 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

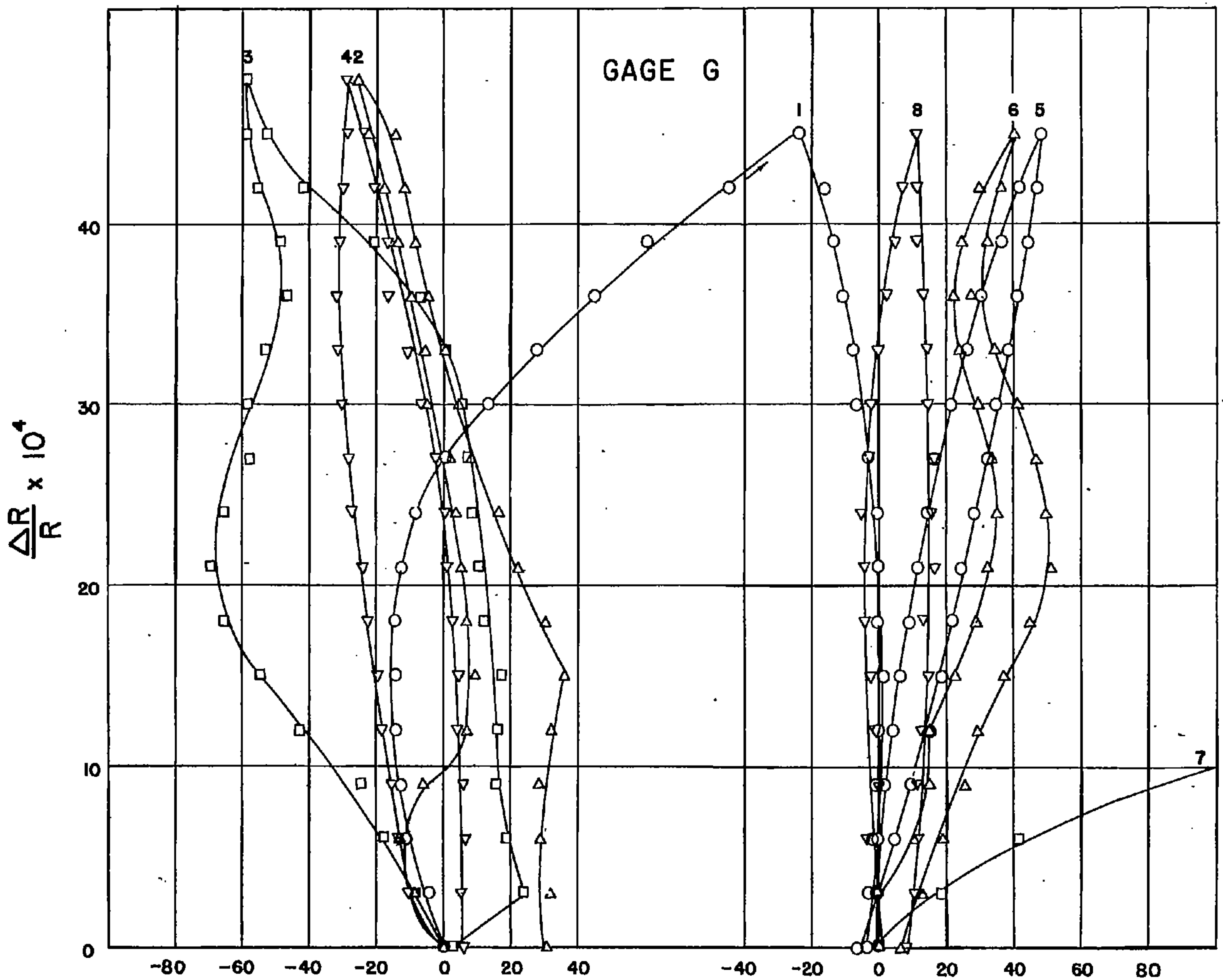


FIG. 12 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

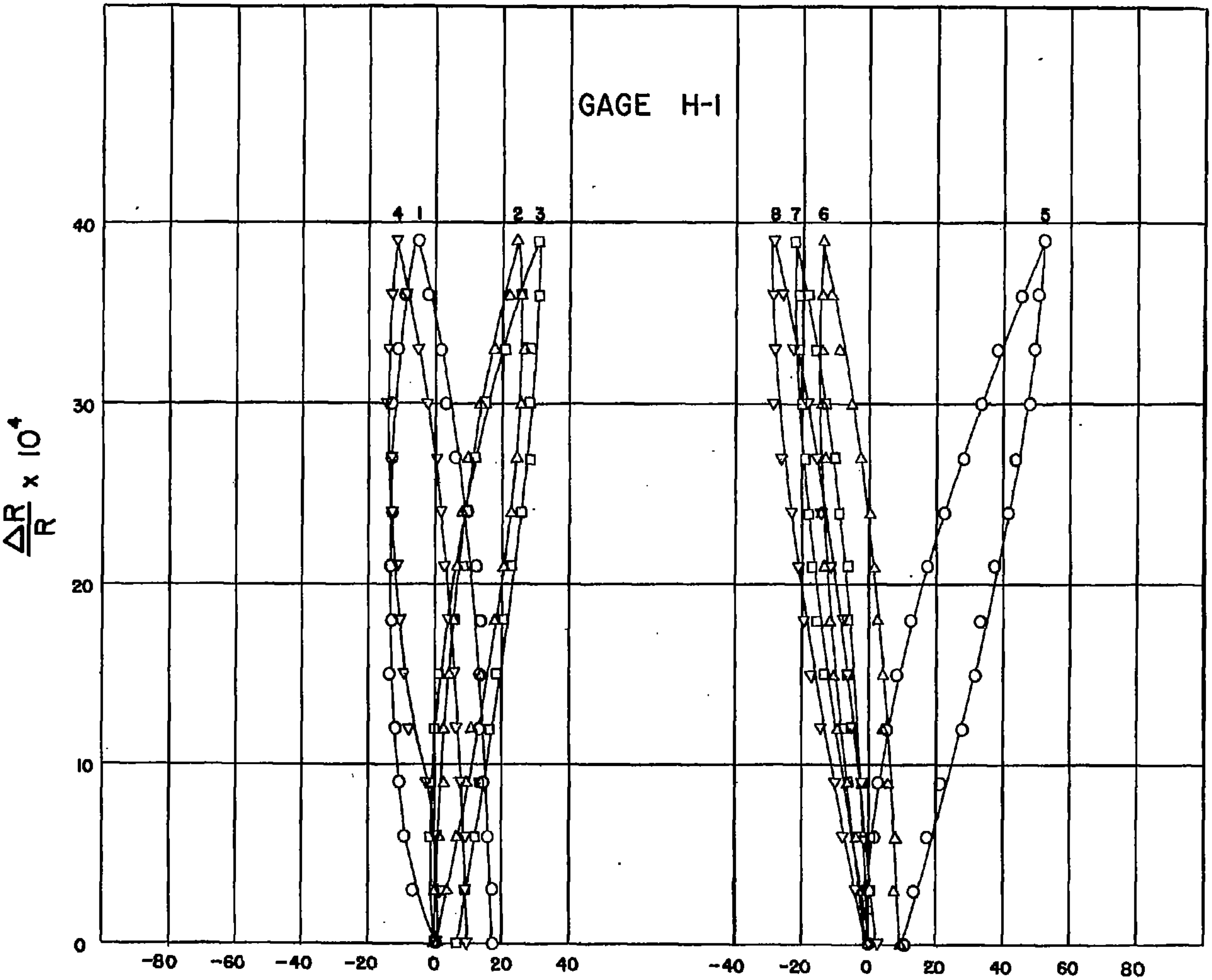


FIG. 13 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

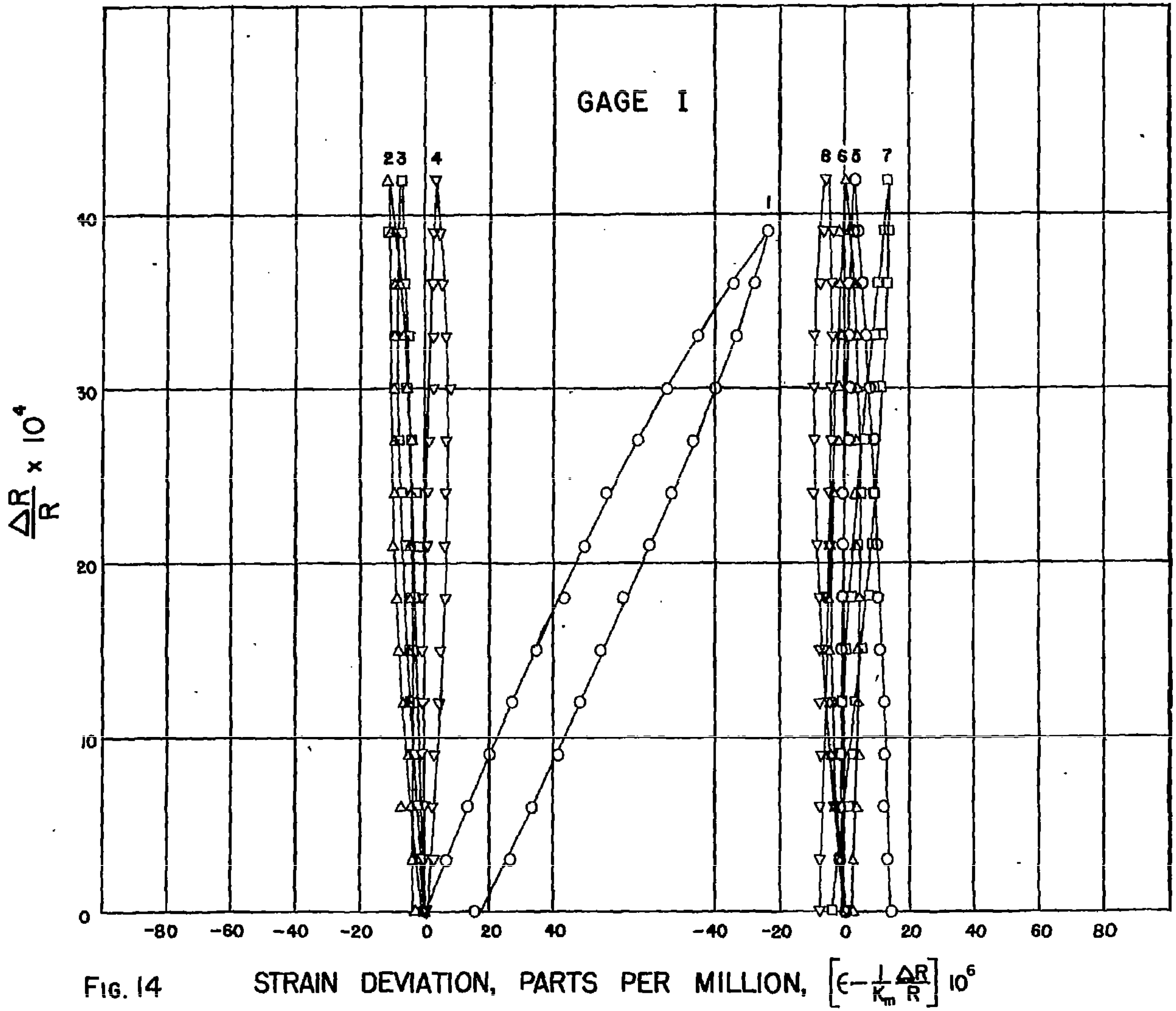

GAGE I
2
3
4
1
8
6
5
7
$\frac{\Delta R}{R} \times 10^4$
0
10
20
30
40
-80
-60
-40
-20
0
20
40
-40
-20
0
20
40
60
80
STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

FIG. 14

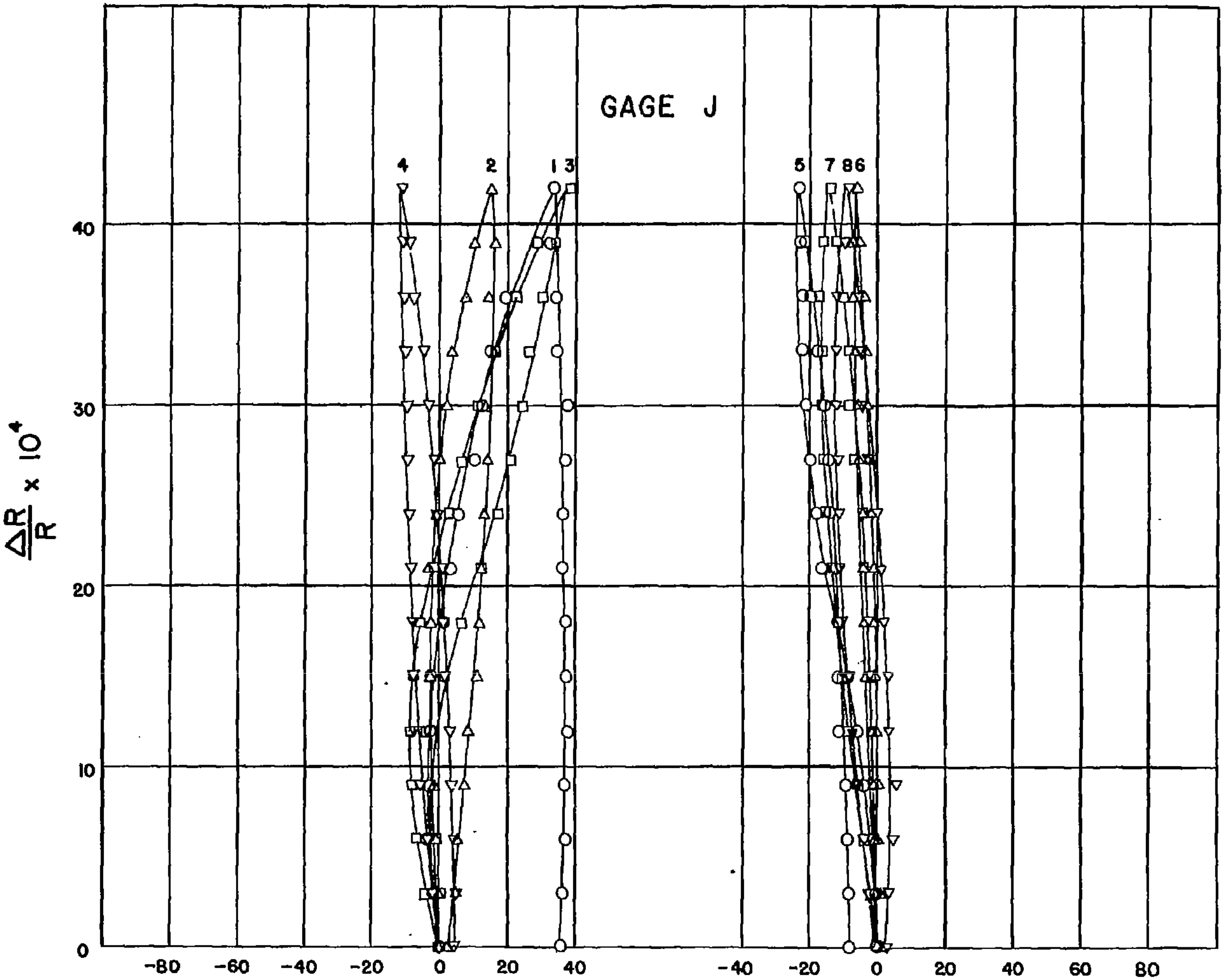


FIG. 15

STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

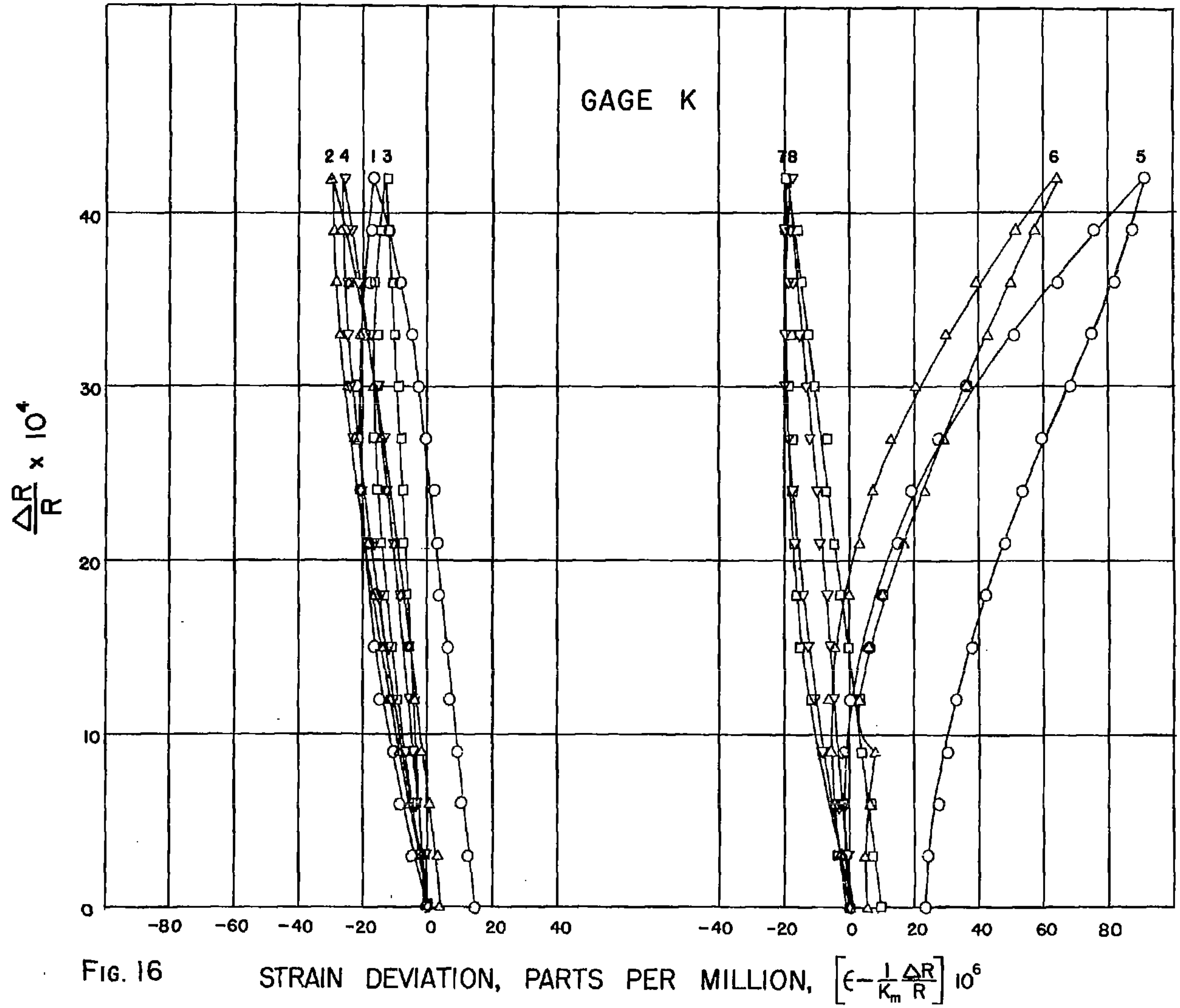

GAGE K
2 4 1 3
7 8
6
5
$\frac{\Delta R}{R} \times 10^4$
0
10
20
30
40
-80 -60 -40 -20 0 20 40
-40 -20 0 20 40 60 80
STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

FIG. 16

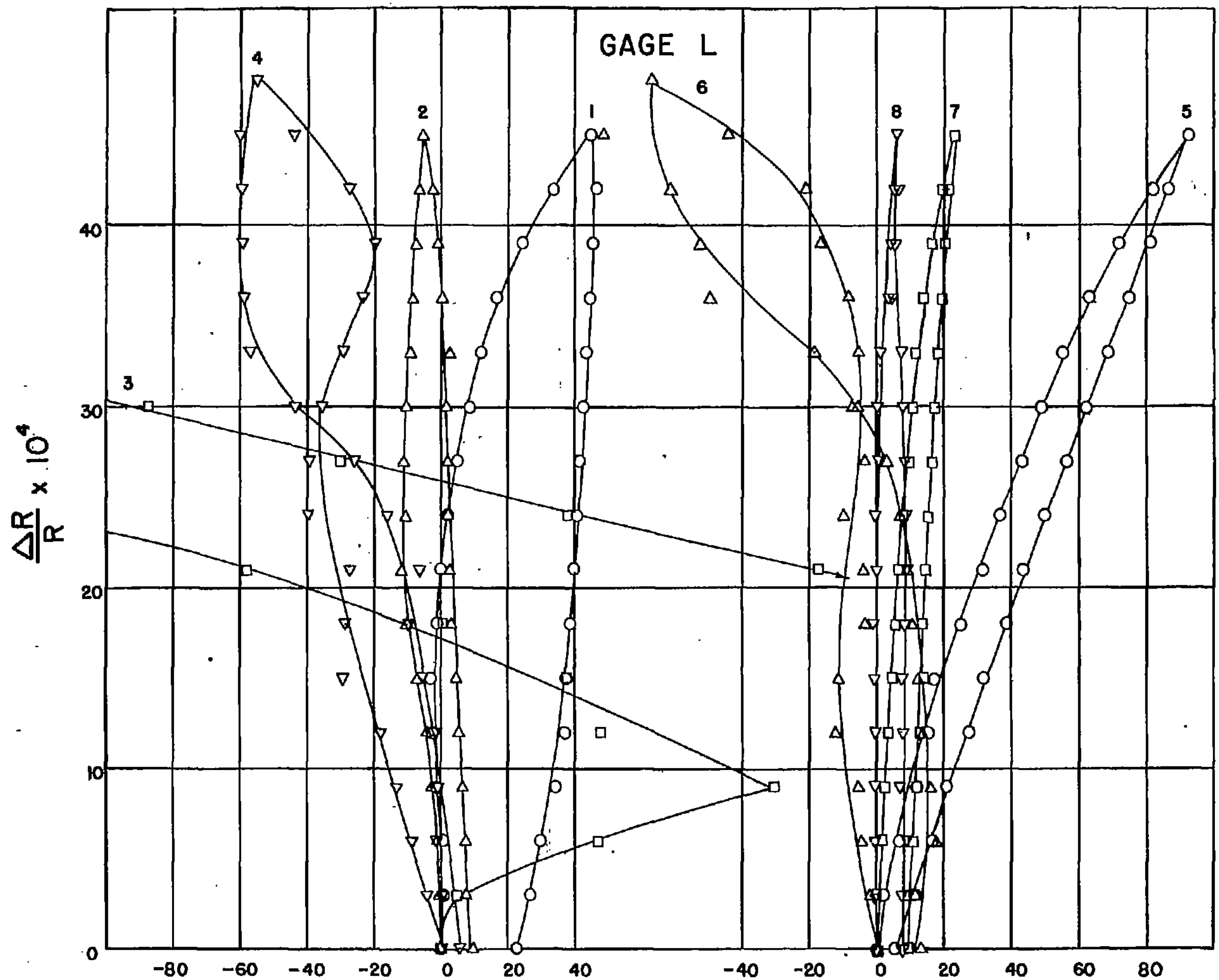


FIG. 17 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

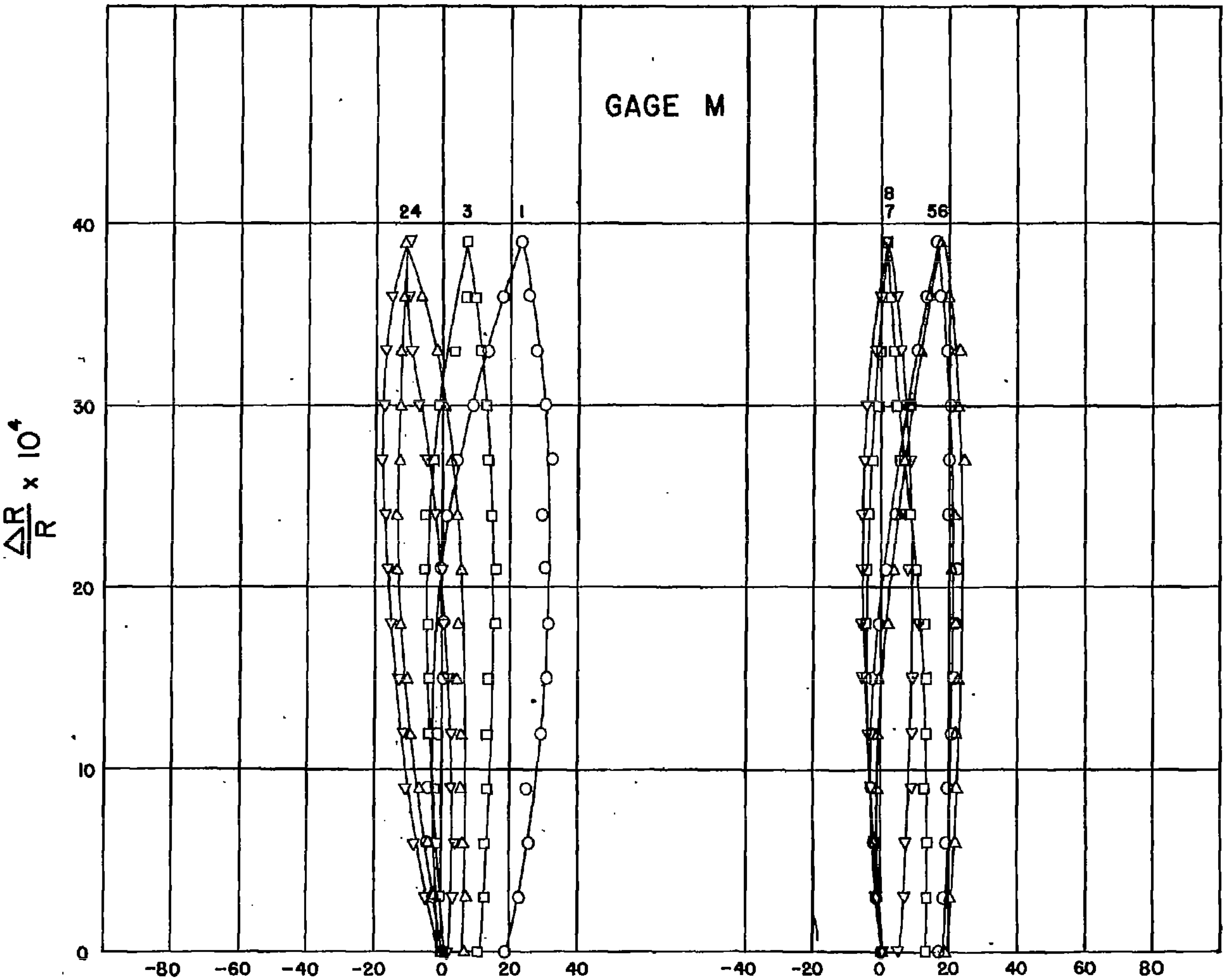


FIG. 18 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

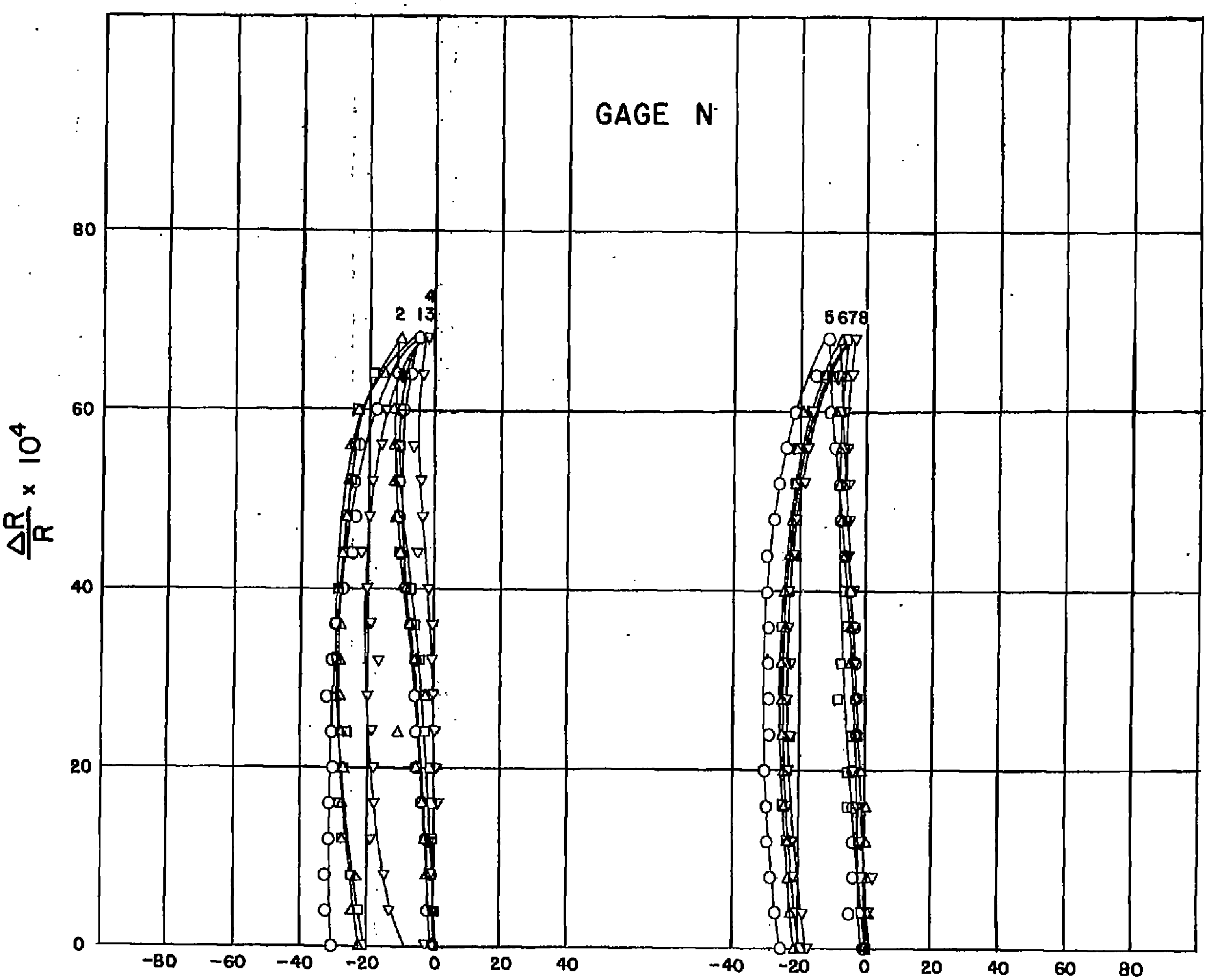


FIG. 19 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

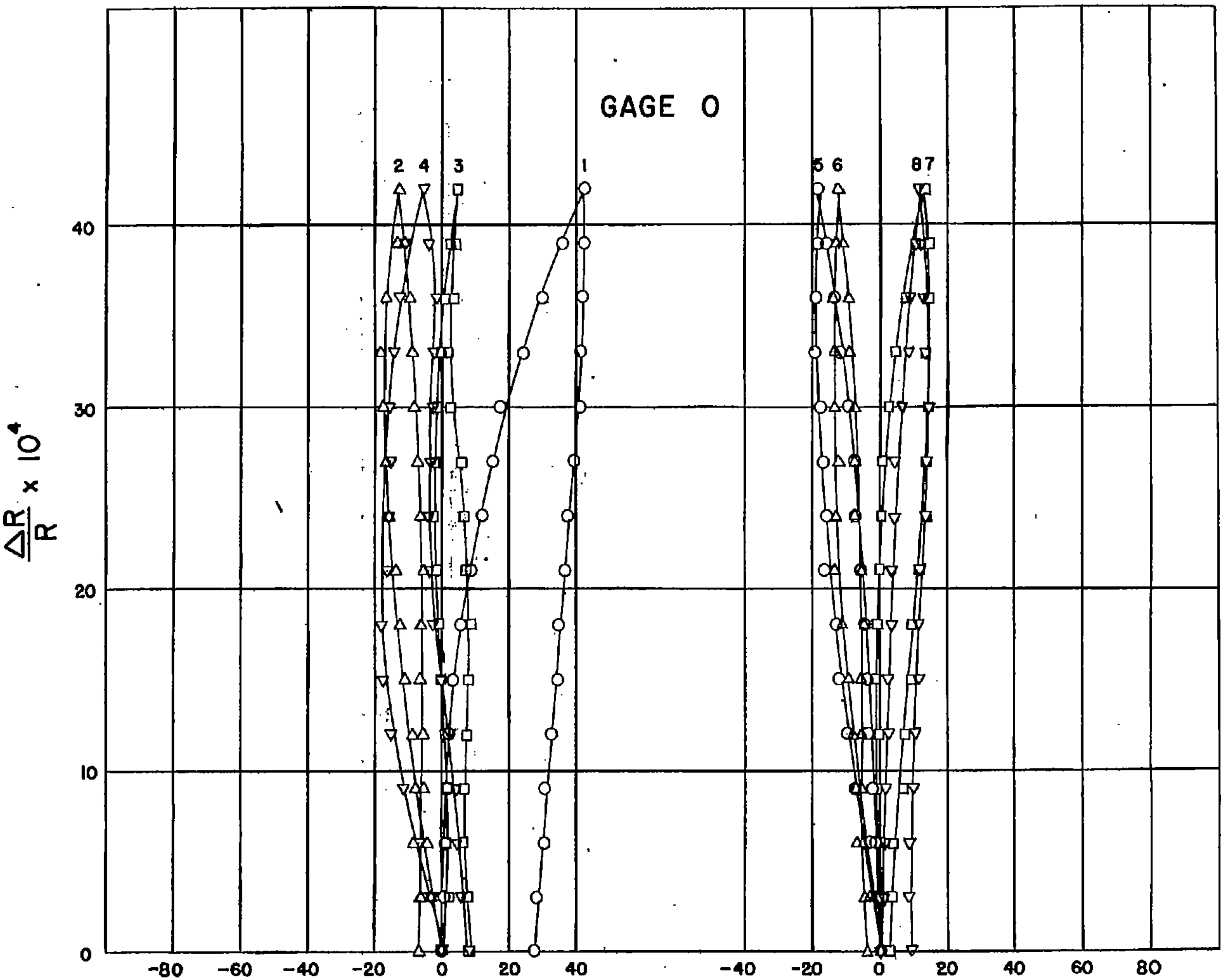


FIG. 20 STRAIN DEVIATION, PARTS PER MILLION, $\left[\epsilon - \frac{1}{K_m}\frac{\Delta R}{R}\right] 10^6$

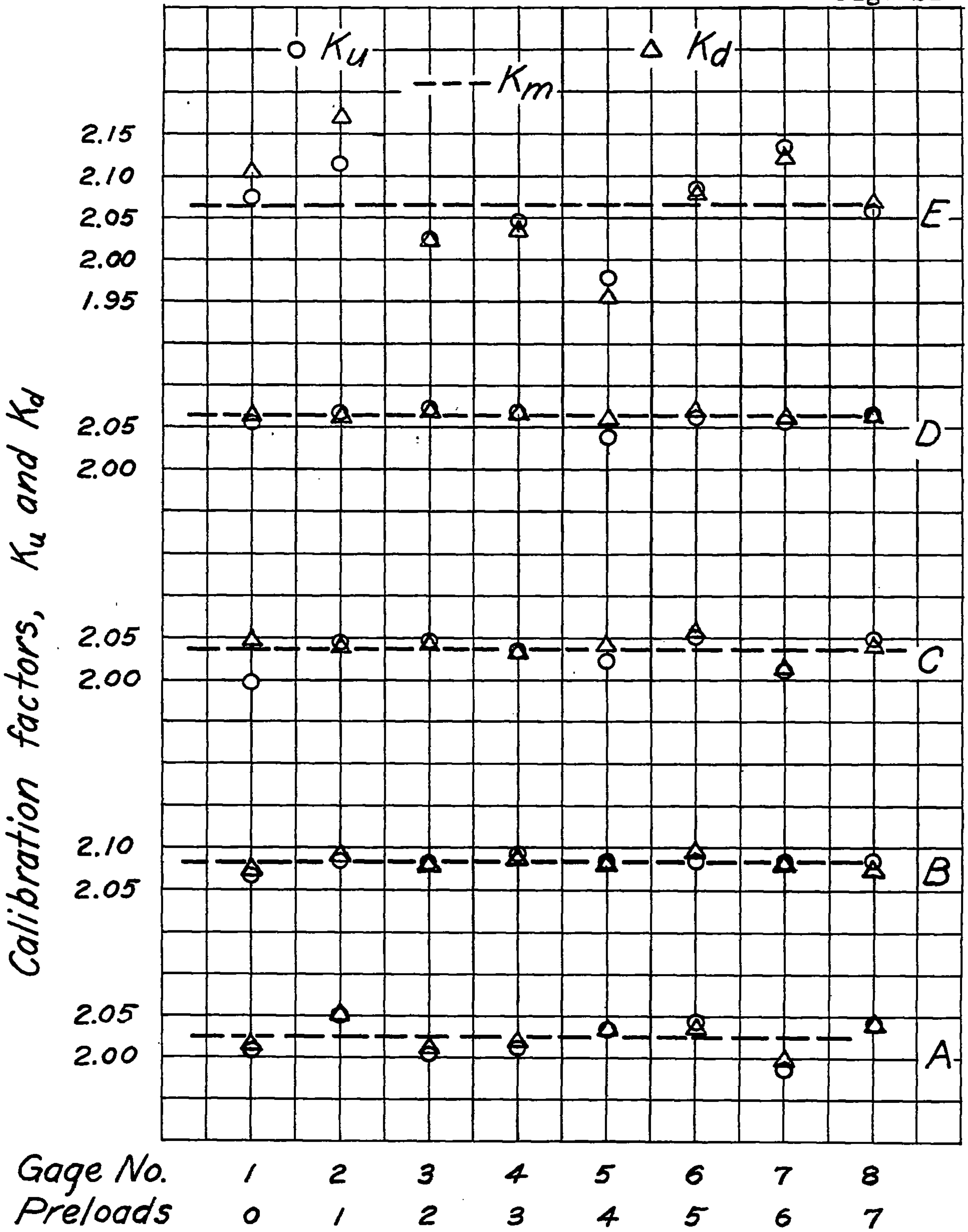


Figure 21.— Calibration factors against gage number and preloads.

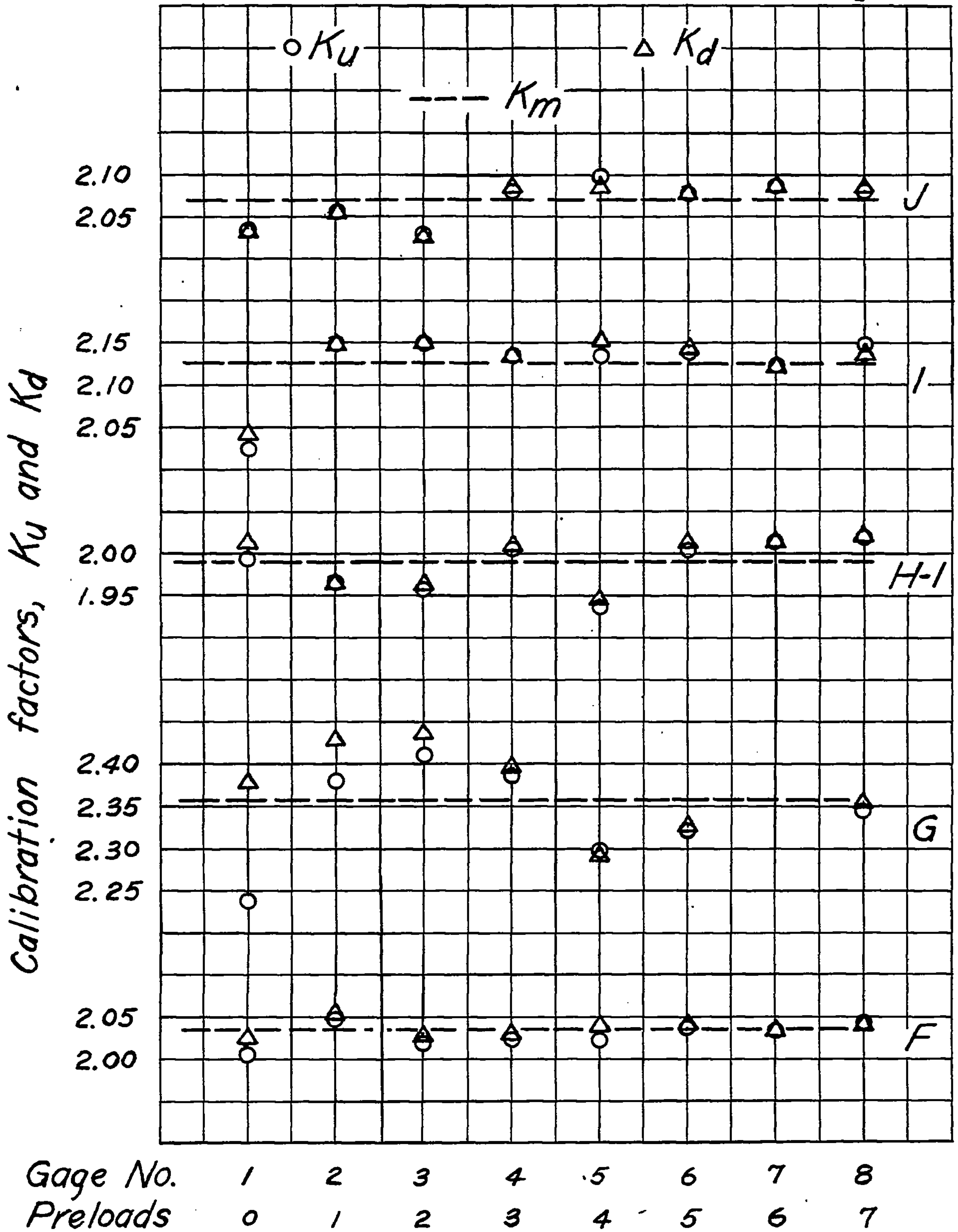


Figure 22.- Calibration factors against gage number and preloads.

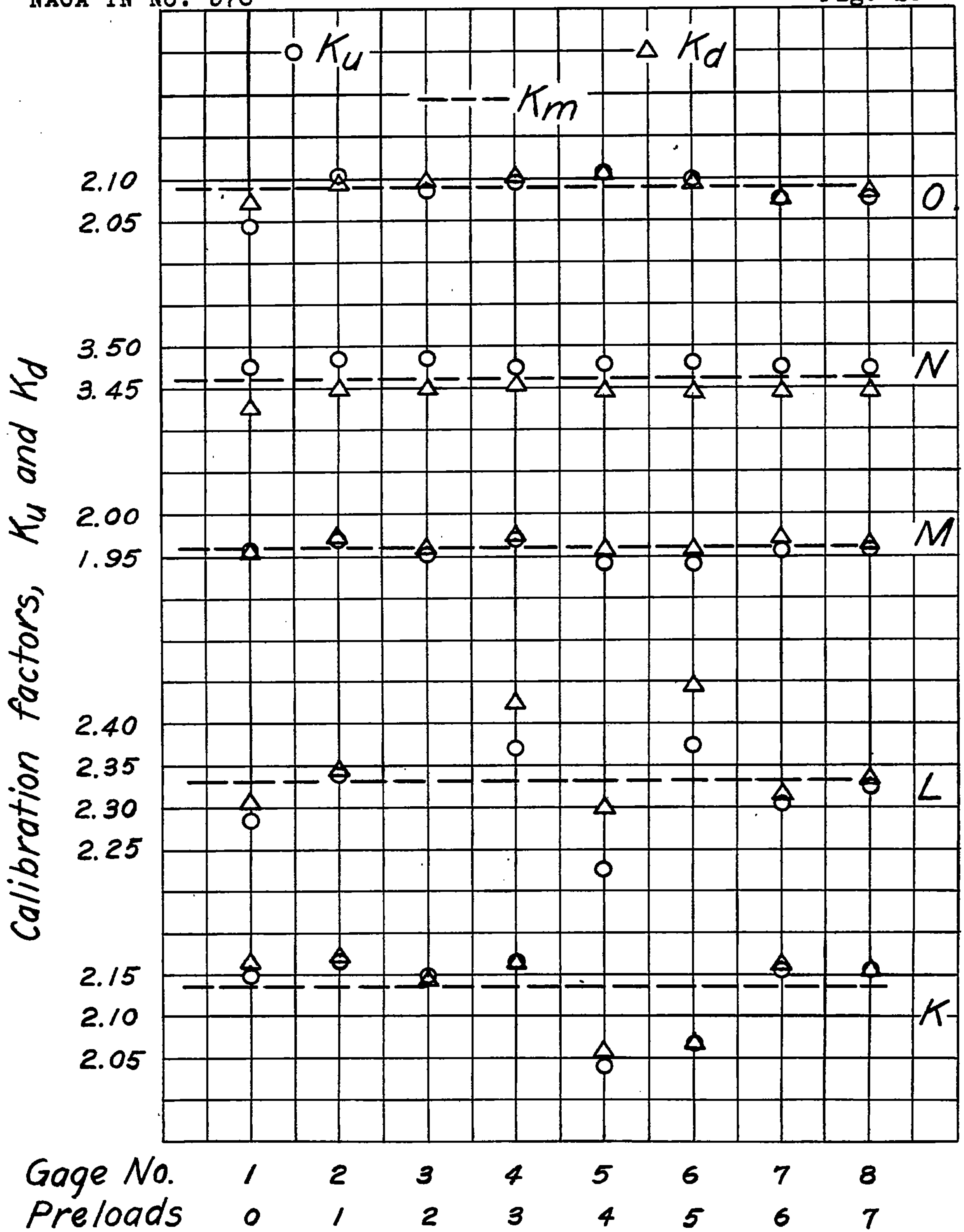


Figure 23.— Calibration factors against gage number and preloads.

Figure 24.- Test gages of type H-1 attached to test column (cover on gage at right removed).